Global Climate Modeling: The Role of the Oceanic Meridional Overturning Circulation

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The stability of the Earth's climate largely depends on the steadiness with which the ocean and atmosphere transport up to 4 petawatts of thermal energy from low to high latitudes. The thermally driven meridional overturning circulation (MOC) in the ocean carries approximately one-third of this heat, making it a major player in the climate system. Observing the MOC is an expensive undertaking, and while a consistent picture of the mean MOC (dubbed the conveyor belt) has begun to emerge, hardly anything is known about its fluctuations and their effects on the climate.

In an effort to gain an understanding of the stability of the MOC, both in physical and mathematical terms, we have joined with staff from the Advanced Computing Laboratory, Theoretical Division, and Applied Physics Division to begin to simulate the MOC and its variability in two numerically dissimilar ocean models. The most important difference between the two models is their treatment of water depth and density as dependent and independent variables. The POP (Parallel Ocean Program) model, developed at Los Alamos, discretizes the ocean in depth space and solves prognostic equations for density. MICOM (Miami Isopycnic Coordinate Ocean Model) developed at the University of Miami, discretizes the ocean in density space and solves prognostic equations for the depth of density surfaces. While both models obey the same physics laws, their numerical representation is distinctly different.

Running two numerically dissimilar ocean models side by side will help us distinguish physically "real" sensitivities and fluctuations in the simulated MOC from model-generated ones. By not depending on a single model architecture with its specific shortcomings, we will be able to proceed more confidently as we set out to investigate interaction modes in the coupled atmosphere-ocean system whose understanding is a prerequisite for multiyear climate prediction. To extend the model diversity to the atmospheric component of climate models, we are working with NASA, Florida State University, and the Southampton Oceanography Centre to couple MICOM to their respective atmospheric circulation models.

This year, our coupled ocean-atmosphere modeling involving MICOM and its sister code, HYCOM, began to yield realistic equilibrium solutions not marred by breakdowns of the MOC seen in early coupling experiments. Because MICOM maintains water mass contrast over long periods of time, we were able to generate computer renditions of the MOC that compare favorably with observations. Our latest estimate of global warming that results from a doubling of CO_2 is a 2°C rise in global surface temperature.

Modeling the Global Ocean Circulation with MICOM

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Flow in the interior of the ocean is nearly adiabatic, allowing oceanographers to track heat-carrying water masses on their centuries-long journey through the world's ocean basins by monitoring their temperature and salinity. Similarly faithful preservation of water-mass characteristics in ocean circulation models is desirable, if not essential, if one wants to reduce trends in oceanic heat content, which, if present, interfere with a coupled atmosphere-ocean model's ability to make meaningful climate predictions.

In this project, we are testing numerical and physical refinements in MICOM, a code that is unique in that it resolves the three-dimensional structure of the ocean on surfaces of constant entropy rather than constant height. MICOM has a 20-year history and has been embraced by the oceanographic community as a viable alternative to traditional (x,y,z) coordinate circulation models. We are testing MICOM refinements in both coupled ocean-atmosphere settings and ocean-alone applications.

Modeling the Global Ocean Circulation with MICOM

Our recent improvements to MICOM have been both physical and numerical. On the physical side, we removed simplifications to the equation-of-state for sea water, which had blurred the distinction between potential density (density corrected for compressibility effects) and in situ density. We also incorporated the Los Alamos sea-ice model into MICOM. On the numerical side, we made considerable progress in generalizing the definition of the vertical coordinate to avoid (1) coordinate surface “outcropping” and (2) the loss of vertical resolution in unstratified ocean basins, both of which are unavoidable in pure isopycnic models. The generalized model, or “hybrid” coordinate sister of MICOM, called HYCOM, is being tested by Los Alamos, NASA, and the Naval Research Lab, where it is viewed as a possible successor to the Navy’s current ocean-prediction model.

At Los Alamos, we are using MICOM and HYCOM to evaluate high-resolution simulations testing the effect of horizontal-grid resolution on climate-relevant processes. This work will help us understand the relative roles of baroclinic eddies and steady ocean currents in transporting heat poleward, a matter of concern when it comes to formulating spatial resolution requirements for future climate models. In 1999, the hybrid grid generator, which is the logic controlling the mix of isopycnal and nonisopycnal coordinate surfaces in HYCOM, reached maturity. Long-term simulations without drift in coordinate representation became possible at this point, confirming HYCOM’s ability to combine the advantages of isopycnal and Cartesian-grid representation in ocean models.

Antarctic Circumpolar Wave and El Niño

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El Niño, which originates in the tropical eastern Pacific and occurs aperiodically, has profound consequences for weather around the globe; consequently, predicting El Niño–caused events is now the focus of a major scientific initiative. Present theory says that the weakening of Walker Circulation (east-west-oriented vertical atmospheric circulation) causes El Niño; when a water mass with warm sea-surface temperature comes into the eastern Pacific, an El Niño occurs. We are investigating the origin of this water mass. We hypothesize that the source of the water mass is the southeast Pacific, as part of the Southern Ocean, which contains the strong eastward flow of the Antarctic circumpolar current. Our objective is to explain the occurrence, triggering mechanism, and aperiodicity of El Niño and to understand the origination of and the atmospheric and oceanic processes in the Antarctic circumpolar wave (ACW).

We used two approaches. First, we analyzed a long time series of observational climate data such as global sea-surface temperature (SST) and mean sea-level pressure (MSLP). Second, we modeled and analyzed our results to supplement and confirm the observational data. Examining global SST anomalies for 1871–1994, we focused on the 32–88 month and 18–35 month windows and found that El Niño had appeared in each of tropical and extratropical basins of North Pacific, South Pacific, Indian, Equatorial Pacific, South Atlantic, and North Atlantic Oceans. According to our analysis, the ACW in southern oceans can influence the occurrence of El Niño in the tropics. We also categorized El Niño life cycles into five patterns: (1) prototype, (2) world-wide, (3) opposite El Niño–La Niña,
(4) north Pacific and south Pacific, and (5) Antarctic circumpolar waves influence. We expect this project to bring us closer to finding the cause of the occurrence of El Niño as well as to provide some insights into the interannual climate variations.

Simulations of Tropospheric Water Vapor with Improved Parameterizations of Deep Convections and Clouds

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Water vapor, the principal greenhouse gas in the atmosphere, plays an important role in climate feedback because of its sensitivity to warming from increasing anthropogenic greenhouse gas emissions. Water-vapor feedback data present many unanswered questions. Would more surface evaporation due to a warmer climate lead to more deep clouds? Would this, in turn, dry or moisten the upper troposphere? Would low-level and high-level clouds also be enhanced? Note, low clouds would cause a negative feedback, and high-level cirrus clouds would cause a positive feedback. Would precipitation and associated evaporation also be changed? It is important to answer these questions before we can tackle the water-vapor problem.

In this project, we are beginning to answer these questions using Los Alamos–developed state-of-the-art parameterizations for clouds and the available data sets. These fundamental problems associated with atmospheric water vapor and clouds include understanding (1) quantification of time rates of change of water vapor and temperature based on two offsetting terms: convection and large-scale circulation; (2) the formation of anvils and cirrus, and (3) the transport of clouds and water vapor by circulation.

Building upon our previous research, we have developed two codes: a hybrid cloud package (SUNAS), which is capable of parameterizing both subgrid-scale cumulus convection and grid-scale clouds; and a cloud-boundary reconstruction scheme (VOF). We have tested the SUNAS package with the VOF method in the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM). The results, based on the single-column version of the model, are encouraging. They indicate that the modeled water vapor distribution in the vertical direction with SUNAS/VOF has a far better agreement with observations than the case without SUNAS/VOF. We hope to conduct a full-blown three-dimensional test of our package at NCAR CCM and we are proposing this to various funding sources.

The Atmospheric Radiation Measurement (ARM) Program in the Tropical Western Pacific (TWP)

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To improve atmospheric models used to predict climate change, parameterizations of important processes, particularly cloud and radiative processes, need to be developed and tested. A key element of the ARM Program of the Department of Energy is to obtain data to help improve and test these parameterizations. Our sites in the TWP location collect data on radiation budget, cloud properties, column water (liquid and vapor), surface meteorology, and vertical structure of the atmosphere. This project is discussed in detail in the Research Highlights section.

Calibrating Climate Instruments for the ARM Program in the TWP

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Climate measurements must be extremely accurate. For example, a 10% inaccuracy in water vapor measurement corresponds to a 3.3 K surface air temperature difference at mid-latitudes. In this project, we are attempting to ensure the best possible accuracy of our instrumentation. Our objective is to go beyond generic accuracy estimates associated with an instrument type and provide quantitative information to assess the performance of a particular instrument at a specific time during the tropical measurements.

EES Division manages the TWP sites for ARM. The tropical sites of Manus Island, New Guinea, the Island of Nauru, and a site we are developing in Darwin, Australia, which are included in the TWP, are ideally located to study the tropical ocean warm pool, but for several reasons it is a challenge to maintain data quality in these remote environments. There are no laboratory facilities nearby, communication is difficult, and the availability of trained personnel is limited. We are developing techniques and procedures to calibrate (when possible), compare, and test climate instrumentation in the field. In addition, we work with ARM program instrument mentors to continually improve the data quality by performing hands-on tests once a year at the sites.

We calibrate these instruments according to the following priorities: the importance of the instrument's measurements, the potential of the instrument for calibration drift, and tropical island logistics. Some of the instruments, such as the millimeter cloud radar, have internal calibration checks that are performed automatically by the instrument and reported with the data. The generic accuracy of each instrument is also known, based on the manufacturers' and users' experiences. Our objective is to provide more specific bounds for the accuracy of each instrument at each location and over specific time intervals. The instruments we calibrate and compare include data loggers, temperature probes, and relative humidity sensors compared with chilled-mirror hygrometers. These results are then used to calibrate the meteorological sensors on towers and balloon sounding systems. Radiometers are calibrated at National Renewable Energy Laboratory in Colorado, and replaced once a year. Simple tests are also performed on the micropulse lidar, the cloud-height ceilometer, and the microwave radiometer for liquid-water and water-vapor measurements.

Theoretical Modeling of High-Altitude Discharges

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In a joint program with Russian researchers, we have investigated a new breakdown mechanism, based on a relativistic electron avalanche that is capable of developing in a weak electric field, when compared to the conventional breakdown threshold. A thorough understanding of this new plasma process is essential for discriminating natural radio-frequency and gamma-ray backgrounds from nuclear explosion signals. In addition, by predicting the associated optical emissions, we can further benchmark our atmospheric simulation codes.

We have applied this mechanism to models of (1) high-altitude optical phenomena known as “red sprites” and “blue jets”; (2) radio-frequency emissions known as TIPPs and CIDs, as recorded on the ALEXIS and FORTE satellites; and (3) gamma rays observed from orbit with the BATSE instrument on the Compton gamma-ray observatory. (TIPP is an acronym for transionospheric pulse pair and CID stands for compact intracloud discharge, a form of lightning.) These models have been published over the last three years and agree well with observations. They simulate the atmosphere from the cloud tops to the ionosphere with a multifluid, electromagnetic equation set. The same theoretical models have recently been used to understand columniform sprites, (temporally brief columns of light just below the ionosphere) by making a connection with meteor showers.

We are currently including this mechanism in our models of normal lightning and are beginning to delineate the regimes in which runaway and conventional breakdown dominate the lightning process. Our Russian colleagues are now analyzing results of experiments designed to measure the avalanche rates, which we both have predicted theoretically and which are a key component in the atmospheric discharge models.

Optical and Chemical Studies of Sulfate Aerosols to Predict Recovery of the Ozone Layer and Constrain the Earth's Radiation Budget

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Ozone depletion and climate change, two very important global environmental problems, continue to challenge atmospheric scientists. Recent international agreements to limit the atmospheric levels of chlorofluorocarbons should result in a gradual decline of ozone loss; however, atmospheric concentrations of greenhouse gases, including CO_2, will likely continue to rise in the near future. Greenhouse gases warm the lower atmosphere but cool the stratosphere by enhancing radiative heat loss to space.

Sulfate aerosols play an important role in both ozone loss and climate change by affecting stratospheric chemistry and radiative transfer, respectively. In our research, we are measuring the physical, optical, and chemical properties of simulated stratospheric sulfate aerosols suspended in gases, using a single-particle balance. Our results will provide improved data for global climate models and enhance the understanding of ozone depletion.

We have made several improvements to the single-particle balance. We modified it to use a photoacoustic method, in which the particle is illuminated by modulated laser light, and the resulting pressure modulation of the gas in the particle trap is determined. We also developed a new technique to inject particles into the balance, incorporated a fiber-coupled laser, and added a photoacoustic detector to the system. In addition, we measured the acoustic characteristics of the trap. The acoustic noise in the laboratory generally increases with frequency and shows a broad peak about 2 kHz. In contrast, acoustic resonances occur in the trap near 300, 500, and 900 Hz. By operating at one of the resonant modes of the trap, we are able to maximize the signal-to-noise of the photoacoustic signal caused by particle absorption. Our results indicate that it is feasible to measure the absorption of particles within the balance. During the next fiscal year we will begin injecting sulfate and mineral particles into the balance and measuring their size and absorption properties. We will then move to more stratospherically relevant particles of mixed sulfate and mineral compositions and measuring their absorption and albedo.

Vertical Transport and Mixing (VTMX): Observations

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The objective of our project is to make spatially resolved images of the surface-atmosphere interface under stable nighttime conditions using the scanning Raman lidar. Recently, in support of VTMX, the experimental team fielded the lidar at the Cooperative Atmosphere-Surface Exchange Studies (CASES) site in Kansas as part of an NCAR project. The lidar was used to measure water-vapor concentration adjacent to a 60-m-high tower with 1.5-m range resolution and 0.5-m vertical resolution.

The VTMX and CASES experiments will be used to observe and measure the turbulent exchange properties of the stable and nocturnal boundary layer. This information will then be used to verify models of the boundary layer and help understand the transport of passive scalars such as dust, bacteria, and various chemicals that might be released in urban environments under nighttime conditions. Databases are being compiled and archived, and our preliminary lidar data have been investigated and found to be acceptable for further analysis.

Regional Modeling for Vertical Transport and Mixing (VTMX)

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Urbanization of the intermountain west is proceeding at a rapid pace, and most of the cities lie in a valley or basin nearly surrounded by higher terrain. This geographical setting, combined with increased emissions and stagnant meteorological conditions, leads to reduced air quality. However, the transport and fate of pollutants under stagnant or stable atmospheric conditions is still relatively poorly understood. Therefore, obtaining a better understanding of the stable boundary layer (SBL) over an urban basin is the goal of the VTMX Program.

Our role in the VTMX Program is to combine data analysis and numerical modeling to investigate three mechanisms hypothesized to play a major role in the transport and mixing within the SBL of a valley or basin. The three mechanisms are (1) the merger and layering of multi-scale radiatively driven flows in complex terrain; (2) the heating and roughness induced by an urban region on flows within a basin; and (3) air mass advection into the basin due to changing synoptic conditions. We are analyzing existing data sets to determine how the vertical structure of the SBL over a basin evolves under the influence of these mechanisms. Following the October 2000 VTMX experiment in Salt Lake City, we will examine the vertical profiling, lidar volume imaging, and ancillary ground station measurements. The experiment will provide data on cross-basin mixing caused by side canyon influences and along-basin influences caused by the urban canopy. We intend to use these data to observe the 3-D behavior of flow merger and layering. We will also look specifically at the effects of the heat and roughness of the urban center of Salt Lake City on the vertical structure and compare this with rural soundings.

In our numerical modeling studies, we are simulating the specific phenomena that produce the characteristic vertical structure of basin SBLs. In simulations with idealized basin topography, we are investigating the influence of cold air draining from side canyons into a mountain basin. Early results indicate that the depth and strength of the stable layer in the basin affects the type of vertical motions that result. These and simulations of the Pajarito Plateau are being carried out to study the influence of flow merger and layering on transport and mixing within the stable boundary layer. An urban parameterization will be added to the idealized basin simulations to also determine the role of the urban surface. For our simulations of the El Paso area, we are investigating flow interactions as well as the role of air mass advection due to changing synoptic conditions. Our preliminary simulations indicate that small differences in synoptically influenced low-level winds are important.

Studying Water Vapor in the Atmospheric Surface Layer

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The exchange of water between plant communities and the atmosphere controls, to a large degree, the local recycling of precipitation, an important component of the climate system. To help understand evapotranspiration, we have developed a scanning Raman lidar system that directly measures small-scale variations in water vapor over different surfaces, such as tree canopies and grasslands. This project is discussed in detail in the Research Highlights section.

HIGRAD Model Development and Application

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We are continuing to refine the HIGRAD large-eddy simulation model, and we are applying it to various atmospheric boundary layer problems of interest to the DOE. HIGRAD incorporates advanced numerical methods to solve the Navier-Stokes equations, allowing the code to calculate accurately atmospheric turbulence in conditions involving high gradients on its boundaries and within its domain.

Most recently, an implicit nonlinear algorithm, the Newton-Krylov method, was incorporated into HIGRAD. This method is a combination of a nonlinear outer Newton-based iteration and a linear inner-conjugate residual (Krylov) iteration, but it does not require the explicit formation of the Jacobian matrix. The Newton-Krylov method was used in the simulation of data obtained from the Environmental Protection Agency (EPA) Fluid Modeling Facility wind tunnel, particularly focusing on the 11 x 7 building array and inflow turbulence generation. We have made preliminary analysis of the 11 x 7 building array for mean flow and turbulence quantities on the centerline row (stream-wise direction) of buildings. The data show some significant differences compared to the 2-D array previously tested. We are awaiting the full set of data from EPA. (Off-centerline data will allow the current theories describing the flow to be tested.)

One important application of HIGRAD's capability is the investigation of the dispersion of atmospheric pollutants in urban environments. This work also addresses concerns associated with potential terrorist attacks. Recently, considerable development work took place in setting up HIGRAD to simulate the flow field within the entire Salt Lake City basin. This included developing the ability to zoom in on the flow field over downtown Salt Lake City. The work also included incorporating land use and terrain data into both the radiation and turbulence packages and the development of a simple grid generator. The mechanism to make movies of HIGRAD simulation results was improved. This will provide quicker movie production and hence better ability to visualize plume movement in a complex urban area. A movie of some of our downtown Salt Lake City simulations is in production.

Advances in Microscale Atmospheric Modeling

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We are using new computational models to simulate atmospheric phenomenon associated with strong heat sources and dispersion of contaminants. These new models were designed specifically to deal with the high gradients typical of such situations, and we have been able to model realistically such events as wildfires, Space Shuttle rocket booster explosions, and flow of contaminants around buildings in an urban environment. This project is discussed in detail in the Research Highlights section.